XP-002267943

Dynamic, electronically controlled angle steering of spatial solitons in AlGaAs slab waveguides

L. Friedrich and G. I. Stegeman

Center for Research in Optics and Lasers, University of Central Florida, 4000 Central Florida Boulevard, Orlando, Florida 32816

P. Millar, C. J. Hamilton, and J. S. Aitchison

Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, UK

Received May 29, 1998

We demonstrate experimentally that spatial solitons in AlGaAs slab waveguides can be deflected by an electronically induced prism. We also show that a weak signal beam can be guided and steered by the solitons, thus demonstrating the feasibility of a dynamically reconfigurable optical interconnect.

OCIS codes: 130.4310, 190.5970, 190.3270, 060.1810.

Spatial solitons are solutions of the nonlinear Schrödinger equation that arise as a result of the robust interplay between spatial diffraction and the self-focusing effects of a Kerr-like nonlinearity in a slab waveguide geometry.[1] These solutions are stable in such a (1 + 1)-dimensional geometry, in which diffraction occurs in one transverse beam dimension only, and they have been observed in waveguides made from liquid CS_2, glass, and semiconductors.[2–4] Furthermore, they have some unique properties that make them ideal for novel routing and switching devices with potentially widespread applications in optical telecommunications.[5] For example, it has been demonstrated that a soliton may be spatially steered by introduction of a phase chirp across its phase front and that solitons exhibit a remarkable robustness that makes them resilient against perturbations.[5–7] Moreover, a weak signal beam can be guided within the potential well created by the soliton, which makes it possible to transmit signal beams of orthogonal polarization or different wavelengths within soliton-induced waveguides. Thus one can realize a $1 \times N$ interconnect by guiding the signal within a soliton that is dynamically steered to address N different output ports.[5] In this Letter we report the demonstration of the basic building block of such an interconnect, i.e., a device that electronically imposes a phase chirp upon a spatial soliton, thus achieving controllable angle steering of the soliton and the signal beam guided within the soliton.

The material of choice for our demonstration was AlGaAs, which combines a number of properties favorable for this experiment. High-quality samples can be grown by molecular beam epitaxy. We can vary the index of the material by changing the relative composition of Al and Ga, thus making optical waveguide structures. Moreover, it is well known that AlGaAs exhibits an enhanced Kerr nonlinearity just below half the bandgap that can be designed to fall into the 1.55-μm telecommuncations band. The nonlinearity is such that one can launch a TE polarization, a TM polarization, or any linear combination to form a soliton.[8,9]

The waveguide structure consisted of an undoped 1-μm-thick region of $Al_{0.18}Ga_{0.82}As$ (n = 3.336), sandwiched between 1.5 μm of upper cladding ($Al_{0.30}Ga_{0.70}As$, $n = 3.29$) and 4.0 μm of lower cladding ($Al_{0.40}Ga_{0.60}As$, $n = 3.22$) on top of a GaAs substrate. The resulting waveguide was single mode at a wavelength of 1.55 μm. The upper cladding was p doped, except for a 0.5-μm layer directly adjacent to the core, whereas the lower cladding was n doped (again with the exception of the 0.5 μm next to the core). By backspacing the doping layers we kept the waveguide losses to a minimum. Thus the device could be used as a diode in the direction perpendicular to the waveguiding film. The effective thickness of the slab waveguide was 1.8 μm. The effective nonlinear index of the material was 1.3×10^{-13} cm^2/W, and the waveguide loss was 0.1–0.15 cm^{-1} (all parameters given at 1.55-μm wavelength). On top of the device a heavily p-doped layer of 0.1-μm thickness was formed and photolithographically processed so that only wedge-shaped prisms remained. These structures served as the top electrodes, and the substrate formed the bottom electrode. By placing these electrodes in contact and injecting carriers in the forward-bias regime we lowered the index of the AlGaAs, thus creating a (low-index) prism in the material. The prism angles varied from 15.5° to 0.3°, and the prisms were 70 μm wide (see Fig. 1). The sample length varied from 10 to 17 mm.

Experiments were performed with an additively pulse mode-locked color-center laser operating at a wavelength of 1.55 μm, with a pulse width of 500 fs and a repetition rate of 76 MHz. A scanning Fabry–Perot interferometer, a wavemeter, and an autocorrelator were used to monitor the spectrum, wavelength, and temporal shape of the pulse, respectively. The laser beam was shaped to an elliptical spot by a cylindrical telescope. This shaping allowed efficient coupling to the waveguide while simultaneously reducing

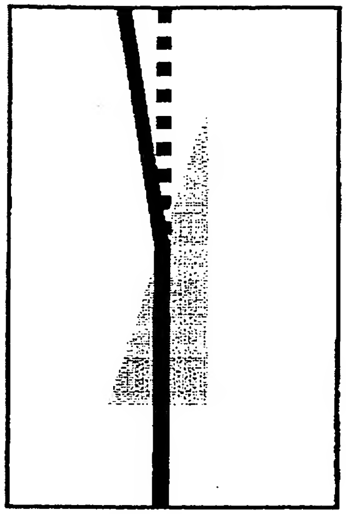

Fig. 1. Top view of the soliton sample, showing a typical electrode (shaded area) and deflected (solid line) and undeflected (dashed line) spatial solitons.

diffraction in the unconfined dimension, thus reducing the power required for soliton formation. A 40× microscope objective was used to couple the light into the waveguide. We then imaged the end face of the waveguide onto an IR camera and a detector, using a 20× microscope objective. Input power was varied by a half-wave plate–polarizer combination. In these experiments the polarization of the beam forming the soliton was TE, and the signal beam was TM polarized. The $1/e^2$ half-width of the input spot in the plane of the waveguide where diffraction occurred was 30 μm. This corresponds to a diffraction length of 6 mm; i.e., the samples were 1.6 to 2.8 diffraction lengths long. The results shown here were obtained by use of the shortest sample, as it proved difficult to place the longer samples in contact electronically. The spot size in the other direction was 1.5 μm ($1/e^2$ half-width), which resulted in a cw soliton power of approximately 200 W. However, the measured value was ~300 W, which corresponds to earlier results[6] and reflects the fact that the soliton power is calculated for the cw case, whereas the laser is operated in the pulsed mode. Examples of both the diffracted beam and the soliton are shown in Fig. 2.

The soliton was launched so that it passed underneath the wedge-shaped electrode, i.e., through the waveguide prism. The resulting spatially anisotropic phase change caused the soliton to be deflected. When the whole width of the soliton is experiencing a phase change, the deflection is correctly predicted by Snell's law.[6] Because the index change in the material is proportional to the injected current, we steered the soliton dynamically by simply adjusting the current.

We achieved deflection of the soliton by injecting currents of as much 500 mA via the top electrodes in the forward-biased regime. The prism created by the injected carriers deflected the soliton position at the output facet. The soliton profile remained intact while it was being deflected, as we verified by monitoring the beam shape at the output facet. A maximum lateral deflection of ~30 μm was obtained at the output face for the current sample design, which corresponds to roughly one FWHM of the soliton beam and an index change of approximately -1.6×10^{-4}. The maximum deflection was obtained under the prism with the smallest prism angle (0.3°) and was limited by both the sample length and the maximum current that could be injected without damaging the contact pad. As expected, the deflection effect was independent of the polarization of the soliton. A weak signal beam (signal/soliton power ratio, 0.03) of the opposite polarization (i.e., TM) but the same wavelength was then guided and deflected within the soliton. Figure 3 shows the results of this experiment after the soliton beam was filtered out with a polarizer. The beam profile of the signal beam is basically identical to that of the soliton itself owing to the self-consistent nature of the soliton and the soliton-created waveguide. The steered beam experienced no significantly higher losses owing to free-carrier absorption arising from the injected carriers. This finding can be seen in Fig. 3, which shows the results when steered and unsteered signal beams of equal power were launched. At the output face both beams still had the same power, as shown in the figure.

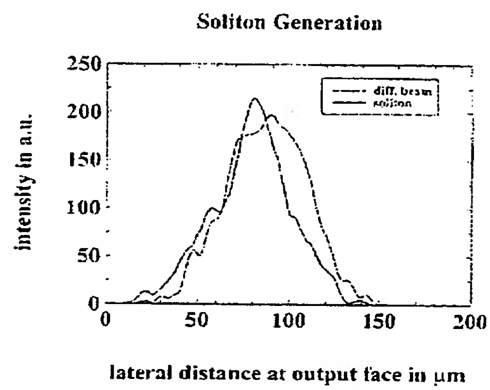

Fig. 2. Diffracted beam and soliton line scan.

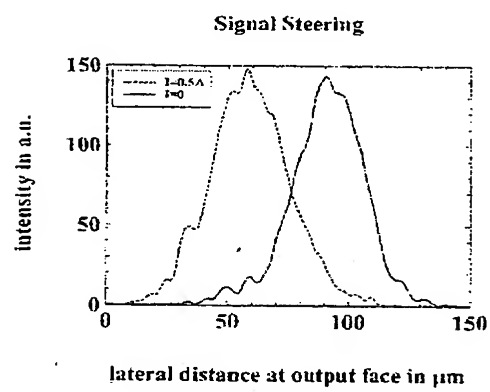

Fig. 3. Line scan showing the deflection and guiding of a weak signal beam inside a spatial soliton.

Finally, we attempted to induce an index change through the electro-optic effect by using the diode in the reverse-bias regime. Breakdown occurred at ~9 V. Assuming that the whole voltage drop takes place across the undoped 2 μm that contains the waveguide core, fields of as much as 4.5×10^6 V/m could be obtained. An interesting feature of the electro-optic effect in this material is its polarization dependence; i.e., only TE beams experience the index change. However, the deflections that were obtained were small and could barely be observed.

In conclusion, we have carried out experiments that demonstrated the dynamic steering of spatial solitons by use of electronically induced index changes. The index changes were obtained in prism-shaped regions by injection of carriers through appropriately formed electrodes. Weak signal beams of orthogonal polarization were guided in the potential well created by the solitons, thus showing the feasibility of a dynamically reconfigurable optical interconnect.

This research at the Center for Research in Optics and Lasers was supported in the United States by the Ballistic Missile Defense Organization and the U.S. Air Force Office of Scientific Research and in the UK by the Engineering and Physical Sciences Research Council. J. S. Aitchison thanks the Royal Society of Edinburgh and the Scottish Education Department for a personal research fellowship. L. Friedrich thanks Jin U. Kang for many helpful discussions.

References

1. V. E. Zakharov and A. B. Shabat, Sov. Phys. JETP **34**, 62 (1972).
2. A. Barthelemy, S. Maneuf, and C. Froehly, Opt. Commun. **55**, 201 (1985).
3. J. S. Aitchison, A. M. Weiner, Y. Silberberg, M. K. Oliver, J. L. Jackel, D. E. Leaird, E. M. Vogel, and P. W. E. Smith, Opt. Lett. **15**, 471 (1990).
4. J. S. Aitchison, K. Al-Hemyari, C. N. Ironside, R. S. Grant, and W. Sibbet, Electron. Lett. **28**, 1879 (1992).
5. G. I. Stegeman, P. Mamyshev, W. Torruellas, A. Villeneuve, and J. S. Aitchison, Proc. SPIE **2481**, 270 (1995).
6. J. U. Kang, C. J. Hamiton, J. S. Aitchison, and G. I. Stegeman, Appl. Phys. Lett. **70**, 1363 (1997).
7. C. R. Menyuk, J. Opt. Soc. Am. B **10**, 1585 (1993).
8. J. U. Kang, G. I. Stegeman, J. S. Aitchison, and N. Akhmediev, Phys. Rev. Lett. **76**, 3699 (1996).
9. J. S. Aitchison, D. C. Hutchings, J. U. Kang, G. I. Stegeman, and A. Villeneuve, IEEE J. Quantum Electron. **33**, 341 (1997).